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Lessons Learned from the Source Physics Experiment (SPE) Near Field Data and Associated Modeling Efforts

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Introduction

The Source Physics Experiment (SPE) at the Nevada National Security Site (NNSS) is a series of chemical explosions of different yields and depths of burial performed in different geologic settings to improve our physical understanding and ability to model explosively generated seismic waves, particularly S-waves. Four SPE explosions have been performed to date in the Climax Stock granitic outcrop at NNSS. The shots were well-recorded by an array of over 150 instruments, including both near-field wave motion measurements as well as far-field seismic measurements. This paper describes the main findings of the SPE campaign to date, focusing exclusively on the analysis and modeling of the near-field data, which included triaxial acceleration measurements at many different locations azimuthally distributed around the explosive charge.

Source shape and explosive type have relatively little effect on free field motions

The geometry of the explosive charges used in the source physics experiments are constrained by the diameter of the emplacement hole, which for the first 6 experiments is about 32 in. Thus, as the charge volume increases to accommodate large explosive yields, the length to diameter ratio of the charge also increases. Sensitized Heavy ANFO (SHANFO) was used for the SPE1-3 shots, with a density of 1.32 g/cm^3 and a specific energy of 2.51 kJ/g. However, because the yield of SPE5 (5 tons TNT equivalent) is expected to be 5 times larger than SPE3 and because the borehole size is limited to 32 inches in diameter, using SHANFO in SPE5 would make the canister length (~10 m) comparable to the distances to the near field gauges. The large length-to-diameter (L/D) ratio of the charge can lead to significant perturbations to the free field, affecting both symmetry and non-radial motions. To minimize these geometric effects, a more energetic source is being considered for SPE5 whereby the L/D ratio could be reduced from ~13 to ~7. Since both the type of explosive and the geometry of the source are expected to be significantly different from prior shots in the SPE series, the following two questions arise:

- What effect does changing the explosive type have on the expected ground motions?
- What effect do geometric considerations have on the expected ground motions?

We performed a computational study using GEODYN to determine the effects of charge shape (spherical vs. cylindrical) and charge aspect ratio on ground motions. The main results are shown in Fig. 1, and they indicate that the explosive type has no perceptible effect on the simulated ground motions, with all three explosives investigated (PBXW-114, PBXN-110 and SHANFO) producing nearly identical results. Our simulations also showed that center-initiated, and multi-point initiated cylindrical charges produce results that closely approximate spherical charge performance at ranges of interest (>~10m) for the SPE campaign.

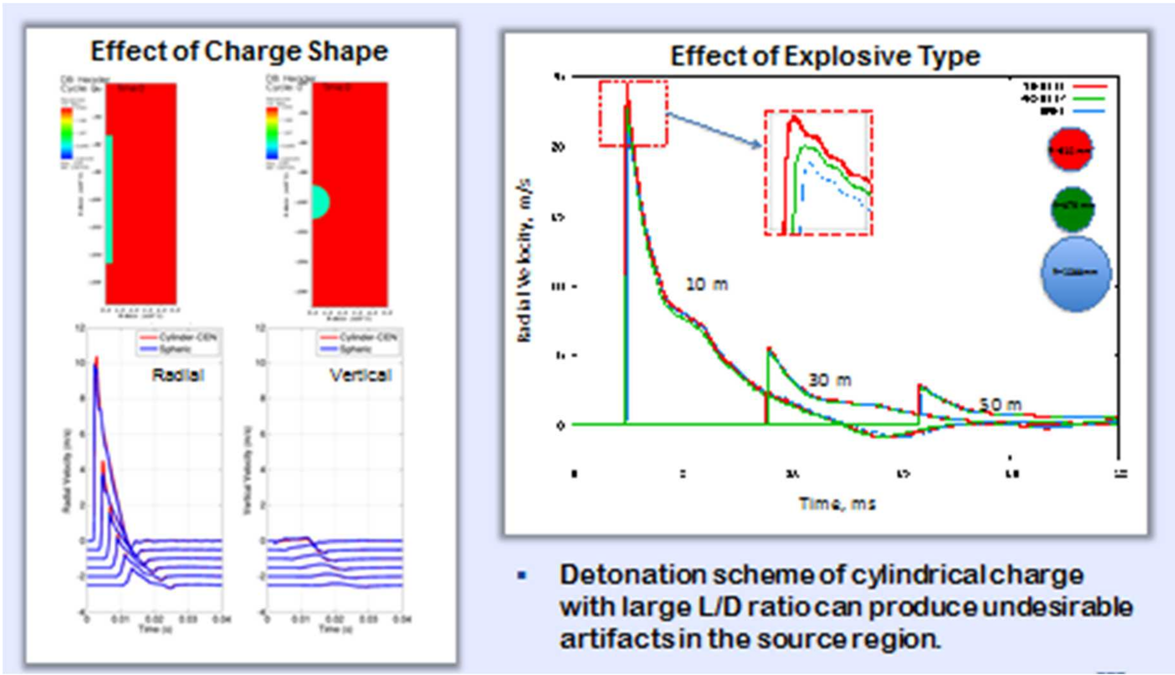

Figure 1. simulated particle velocities for different charge shapes (left panel) and different explosive types (right panel).

It is important to note that since the SPE charges are all cased, we did not consider the interaction of the explosive gases with the fractured rock in the immediate vicinity of the charge. These effects may be important if the experiments are performed with bare explosive charges.

Spatial variability in mechanical properties of granite is not sufficient to explain large non-radial motions observed in the SPE near-field data

One possible source of non-radial motions in the SPE data is spatial variability in mechanical properties such as strength and stiffness. An extensive campaign was undertaken whereby core was extracted from the testbed, and laboratory experiments were performed on core samples from various locations within the testbed. A stochastic approach was used to characterize the variability in mechanical properties in a manner consistent with the laboratory data, and the resultant distributions were used to initialize a suite of hydrodynamic simulations. The tangential motions from these simulations were negligible in all cases, and generally much lower than those observed in the SPE data (Fig. 2).

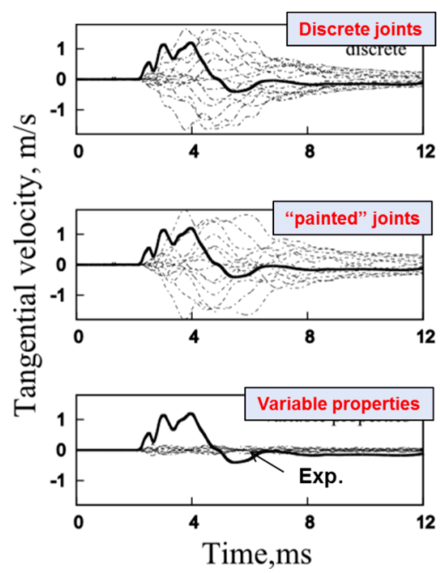

Figure 2. Tangential motions from simulations with discrete joints (top panel), painted joints (middle panel) and variable mechanical properties (bottom panel). The solid line in the figure depicts the experimental data.

Joints and fractures are the primary source of tangential and vertical motions

Another shear wave generation mechanism investigated was motion along pre-existing joints and fractures, which are ubiquitous and preferentially oriented throughout the SPE testbed. Various factors affecting shear wave generation were considered, including joint spacing, orientation and frictional properties. Simulations were performed both in 2-D for a single joint set to elucidate the basic response mechanisms, and in 3-D for multiple joint sets to realistically represent in situ conditions in a realistic geological setting. The joints were modeled explicitly using both contact elements and weakness planes in the material. Simulations were performed both deterministically and stochastically to quantify the effects of geological uncertainties on near field ground motions. The mechanical properties of the rock and the joints as well as the joint spacing and orientation were taken from experimental test data and geophysical logs corresponding to the Climax Stock granitic outcrop, which is the geological setting of the source physics experiment (SPE). This mechanism was found to be the primary source of non-radial motions (Fig. 2), and the results of the simulations, as will be shown later, were found to be in good agreement with SPE measurements. Furthermore, our simulation results indicate that joint properties are critically important to simultaneously predict the attenuation at far ranges and the slow propagation velocities in the weathered surface layer.

A stochastic approach is best suited to describe spatial joint distributions and variability in mechanical properties

Simulations aimed at understanding shear wave generation observed during the SPE underground explosions in fractured granitic rock present several challenges: fractures are poorly characterized and sparsely sampled; and the geomechanical and geophysical properties of both the fractures and intact rock are spatially variable and measured at the laboratory scale. To build a credible model of the subsurface we employed an uncertainty quantification framework within which we integrated the geological, geomechanical and geophysical characterizations conducted at the SPE testbed. Because detailed site characterization is limited we numerically investigated the effects of the characterization gaps on the overall response of the system. Using HPC, we performed several computational studies to identify the key geologic features that affect the most the ground motion in the near-field and in the far-field using stochastic representation of the subsurface. Using brute force Monte Carlo simulations and sampling judiciously the large hyperspace of parameters, we have probabilistically conducted several sensitivity studies on the geological, geomechanical and geophysical parameters. Figure 3 compares measured particle velocity histories from SPE4' with the mean, the upper confidence interval, and the lower confidence interval from the stochastic simulations. As shown, the observed data fall within the 95% confidence interval and in most cases the recorded motion histories are in good agreement (including polarity of shear motion) with the statistical mean of the distribution.

Modeling spall and late time damage require inclusion of gravity and *in situ* stress in the simulations, leading to significant increase in complexity

Spall, a directional tensile damage mechanism associated with the interactions of stress waves with the free surface, can be a plausible mechanism for shear wave generation. Spall damage develops during the upward motion phase near the surface causing separation between the spalled region near the free surface and the rest of the subsurface material affected by the explosion. After the upward motion peaks, a rebound phase ensues whereby the material that had been displaced upward by the explosion will migrate back toward its original position. If no significant damage occurs during the outward motion phase of the explosion, restoring elastic forces will act on the material during the inward motion phase (i.e., rebound) and the medium comes to rest in a time frame comparable to the duration of the explosion. However, if significant damage does occur during the outward motion phase, the rebound phase can no longer be powered by elastic energy, and the spall-damaged material will rebound under gravity at a timescale longer than that of the original explosion by about two orders of magnitude. The disparity in timescales leads to significant complexities, not the least of which is the need for a much larger computational domain and much longer simulation time, an unfortunate combination of constraints that makes these types of simulations very difficult to perform except on modern high performance computing platforms. This fact, combined with the need for uncertainty quantification, which requires many runs to assess statistical variability, makes the simulations performed to support the SPE among the most complex and most extensive geodynamics simulations ever performed.

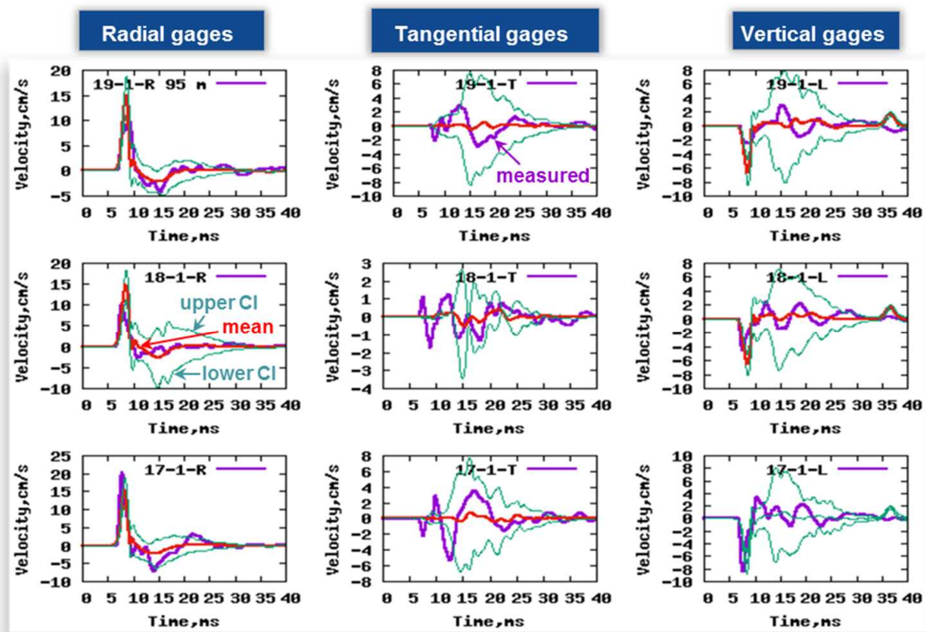

Figure 3. Ground motions from the SPE4' shot recorded at a depth of 99 m and a range 34 m. All three components of particule velocity are shown at three different azimuthally distributed locations along a circumference centered on the charge

Summary and future directions

The Source Physics Experiment has already provided one of the most comprehensive data sets for addressing long standing scientific challenges associated with seismic monitoring of underground nuclear explosions. Specifically in the near field, the extensive logging and characterization efforts have rendered the SPE site as one of the best characterized testbeds in the groundshock literature. As such it is ideally suited for the kind of detailed modeling and analysis that are currently being performed at LLNL and elsewhere to advance the state of the art. This paper attempted to summarize some of the main conclusions so far from our on-going efforts. Detailed descriptions of the data, models and analyses performed to reach the conclusions described here can be found in the open literature, notably the following recent publications:

- Vorobiev, O., S. Ezzedine, T. Antoun and L. Glenn, "On the Generation of Tangential Ground Motion by Underground Explosions in Jointed Rocks," *Geophys. J. Int.,* **200**, 1651–1661 (2015) doi: 10.1093/gji/ggu478

- Ezzedine, S. M.; Vorobiev, O.; Glenn, L.A. and Antoun, T.H, “Application of HPC and Non-Linear Hydrocodes to Uncertainty Quantification in Subsurface Explosion Source Physics,” ARMA 15-568, Proceedings of the 49th US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA, USA, 28 June- 1 July 2015.
- Pitarka, A., R. Mellors, W. Walter, S. Ezzedine, O. Vorobiev, T. Antoun, J. Wagoner, E. Matzel, S. Ford, A. Rodgers, L. Glenn, and M. Pasyanos, “Analysis of Ground Motion from an Underground Chemical Explosion,” *Bulletin of the Seismological Society of America*, **105**(5), 2390–2410, October 2015, doi: 10.1785/0120150066

Recent parametric studies have shown that the presence of joints can have the effect of sustaining and even amplifying shear motion in the far field, which can have significant implications for explosion monitoring. A quantitative assessment of this observation requires a modeling approach that accounts for the effect of joints on wave propagation in both the near- and far- fields. We have initiated efforts to improve the coupling between near- and far-field simulations and to incorporate relevant models and algorithms in our end-to-end modeling platform. Two key enablers of this capability are an anisotropic constitutive model and the ability to calibrate the model by upscaling properties derived from detailed simulations that account for the effect of joints on wave propagation. These efforts are currently underway and will continue in the foreseeable future.

Finally, our efforts to date have focused primarily on shear wave generation in fracture granite (Phase I). As the SPE campaign shifts focus to alluvium (Phase II), so too will our modeling effort as we explore the underlying mechanisms for shear wave generation in alluvium, a distinctly different medium from fractured granite with different shear wave generation mechanisms.

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